HIGHLIGHTS OF ANTENNA HISTORY

JACK RAMSAY

A look at the major events in the development of antennas.

NINETEENTH CENTURY WIRE ANTENNAS

IT is not surprising that wire antennas were inaugurated in 1842 by the inventor of wire telegraphy, Joseph Henry, Professor of Natural Philosophy at Princeton, NJ. By "throwing a spark" to a circuit of wire in an upper room, Henry found that the current received in a parallel circuit in a cellar 30 ft below could magnetize needles. With a vertical wire from his study to the roof of his house, he detected lightning flashes 7-8 mi distant. Henry also sparked to a telegraph wire running from his laboratory to his house, and magnetized needles in a coil attached to a parallel wire 220 ft away. Later experiments may have extended the range to half a mile.

The magnetization of the detecting needle by the remote discharge was not always in the same direction. Henry deduced "the existence of a principal discharge in one direction, and then several reflex actions backward and forward, each more feeble than the preceding, until the equilibrium is obtained." He later commented, "As these are the results of currents in alternate directions, they must produce in surrounding space a series of plus and minus motions analogous to if not identical with undulations." In 1842 he had "inferred that the diffusion of motion in this case is almost comparable with that of a spark from a flint and steel in the case of light." Clearly Joseph Henry had discovered electromagnetic waves, and even formulated the idea that light waves were of this type.

In 1875 Edison discovered that keyclicks radiated to a distance, and in 1885 he patented a communication system (Fig. 1) using vertical, top-loaded, grounded antennas. He also suggested the use of captive balloons to support long wires. Antenna systems similar to Edison's were used by A. E. Dolbear in 1882 when he successfully and somewhat mysteriously succeeded in transmitting code and even speech to significant ranges, allegedly by ground conduction. However, in one experiment he actually flew the first kite antenna. About the same time, the Irish professor, G. F. Fitzgerald, calculated that a loop would radiate and that a capacitance connected to a resistor would radiate at VHF (undoubtedly due to radiation from the wire connecting leads).

In 1887 H. Hertz launched, processed, and received radio waves systematically. He used a balanced or dipole antenna attached to an induction coil as a transmitter, and a one-turn loop (rectangular) containing a spark gap as a receiver. He obtained "sympathetic resonance" by tuning the dipole with sliding spheres, and the loop by adding series inductance and shunt capacitance, and detected higher modes in the loop. He also invented the plane grating of parallel wires, and established the fundamentals of polarization.

Four major advances in antennas were patented in 1897 by Oliver J. Lodge, Professor of Physics at Liverpool, England. 1) The dipole was made biconical (Fig. 2), 2) a central loading-coil was inserted, 3) a tunable *LC* circuit was coupled to the antenna circuit, and 4) a "counterpoise" antenna was invented by the addition of horizontal capacitance to the dipole arms. These contributions yielded matching, tuning, and the reduction of ground losses, and occupy a position of historic importance. Lodge even added the word "impedance" to the language. Marconi had to add Lodge's tuning advances to his vertical, grounded antennas, with or without top capacitance, to escape the jamming problem.

Phased arrays were proposed in 1889 by: 1) Chicago-born Sydney George Brown, and 2) Dr. James Erskine-Murray, F.I.R.E., the Scottish radio pioneer and assistant to Marconi. The first successful two-element (receiving) array did not appear, however, until about 1906.

In the next section, an account will be given of late nineteenth century microwave antennas, and will show how many basic quasi-optical (another word due to Lodge) antennas and techniques were developed, and lay forgotten for 40 years.

This is reprinted with permission from *The Pulse*, the publication of the Long Island Section of the IEEE. This article originated as a series of one-page monographs in 1969, and covers the period 1842-1969. Jack Ramsay is a Life Fellow of the IEEE and of the IEE, having joined both institutions in 1927. Since then much of his career has been devoted to antennas. He published over 60 papers and is named in 12 U.S. patents and 29 U.K. patents. He resides in Syracuse, NY.

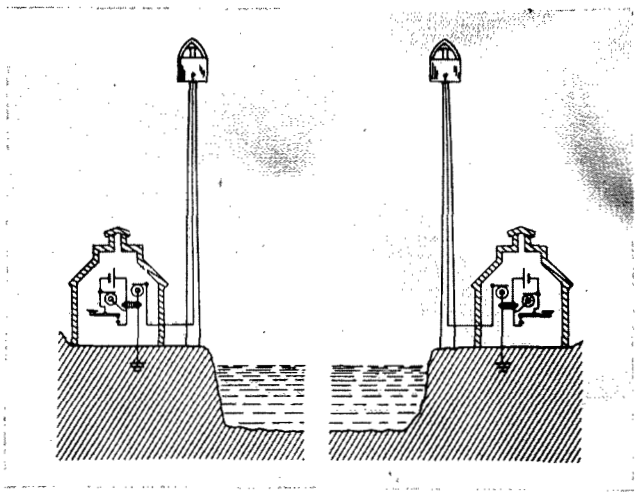


Fig. 1. Edison's antennas (1885).

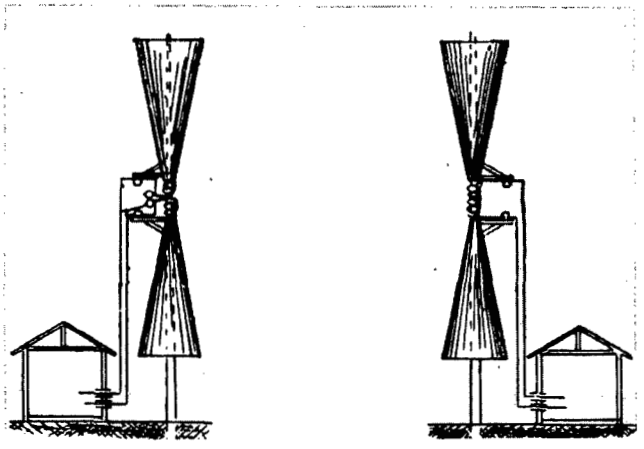


Fig. 2. Lodge's tuned biconical antennas for electric wave telegraphy (1897).

NINETEENTH CENTURY MICROWAVE ANTENNAS

Parabolic reflectors, lenses, horn antennas, and waveguide radiators were used at microwaves before 1900. In 1888 Hertz demonstrated the optical properties of "electric waves" at 66 cm, using cylindrical parabolic antennas. Hertz's discovery of the index of refraction of a pitch prism led Lodge and Howard to construct a pitch lens for 101 cm in 1899. In the nineties Righi used cylindrical reflectors from 2.6 to 21.4 cm. A student of Righi's, Marconi, succeeded in signaling between parabolic antennas at 25 cm in 1895. In India, Bose made a sulphur lens for 5 mm to 2.5 cm for transmitting, and used a horn antenna for receiving, the detector being a semiconducting junction device with a bias voltage!

Both Lodge and Bose worked also with open-ended waveguide radiators, Lodge at 7.5 and 20 cm, and Bose from 5 mm to 2.5 cm. In 1900 Fleming demonstrated a rectangular waveguide feed and a paraffin lens at 20 cm.

As inadequate recognition is nowadays given to the advances made by the pioneers in 1888-1900, salute is made to them here by providing such antenna design data as still exists.

The third section of this series will portray some of the antennas of the early spark radiotelegraphy, 1900-1909.

ANTENNAS FOR THE EARLY SPARK RADIOTELEGRAPHY, 1900-1909

The twentieth century opened auspiciously with Marconi signaling across the Atlantic on December 12, 1901. He used 15 kW and a wavelength of 366 m (820 kHz). Fig. 1 shows the transmitting fan monopole antenna in England. The 48 m masts were 60 m apart. At Newfoundland, emergency kite antennas received the first signals. By 1904 the English antenna had become the pyramidal monopole with umbrella wires (Fig. 2), and the frequency 70 kHz. In 1905 the Canadian antenna was the capacitive structure of Fig. 3, for 82 kHz. There was 200 radials, each 1000 ft long, at a height of 180 ft. Note that in a few years the frequency had dropped by ten times.

Ever since his centimeter-wave communications of 1895, Marconi had believed in the superiority of directive communications, and much of his life was devoted to pursuing this objective. In 1906 he obtained a measure of directivity with long waves, using his "bent antenna" over ground (Fig. 4). The groundwave antenna pattern shown may be the first measured polar diagram that was ever published. The bent antenna was later to evolve into the Alexanderson multiple tuned antenna, the Beverage antenna, the Vee antenna and the Bruce or rhombic antenna, to say nothing of modern surface wave antennas. Marconi's instinct for making the right creative contribution at the right time always had the stamp of genius.

In Italy others were interested in directivity, as were J. Stone Stone and DeForest in the U.S.A. Following S. G. Brown's suggestion of 1899, Artom, in 1906, published in Italy a description of a successful phased pair of antennas for reception (Fig. 5). In the following year Bellini and Tosi showed that by using two orthogonal pairs with a lumped circuit "goniometer," direction finding was feasible without antenna rotation. Later, in 1912, Prince in the U.S., devised a closed loop version of the B-T antenna (Fig. 6). The long waves used in those days prevented the use of the half-wave spacing desired for arrays, which disappeared for about 20 years.

Conducting ground systems began to appear towards the end of the decade. These usually consisted of radial wires fanning to a ring of buried, bolted plates, forming a cylinder. Actual measurements proved that these ground systems reduced the antenna ground loss resistance. A classic paper by Zenneck in 1907 introduced the theory of electromagnetic wave propagation along a ground-air interface.

The fourth section of this series will describe the continuing evolution of antennas for high power long wave radiotelegraphy, and the significant return to short wave reflectors initiated during World War I.

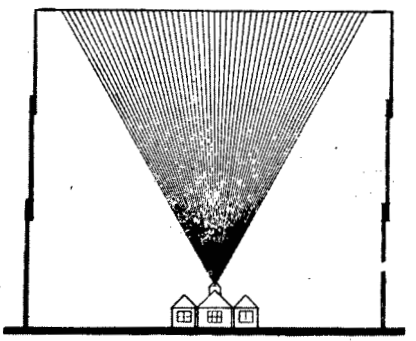


Fig. 1. Fan monopole (Marconi, 1901).

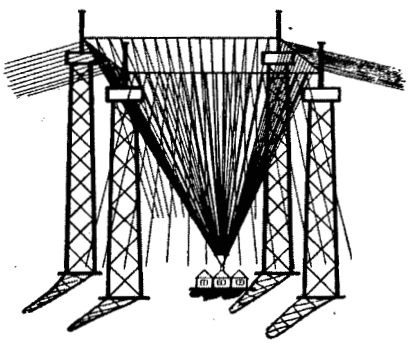


Fig. 2. Umbrella wires on pyramidal stub antenna for 70 kHz (Marconi, 1904).

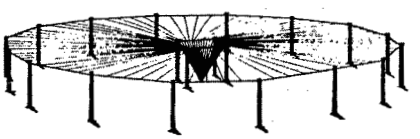


Fig. 3. Capacitive antenna for 82 kHz (Marconi, 1905).

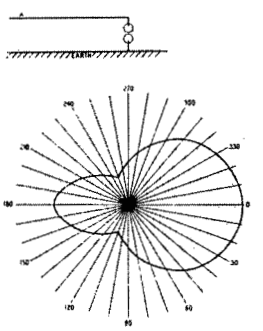


Fig. 4. First ever measured polar diagram? Pattern of Marconi's bent antenna (1905).

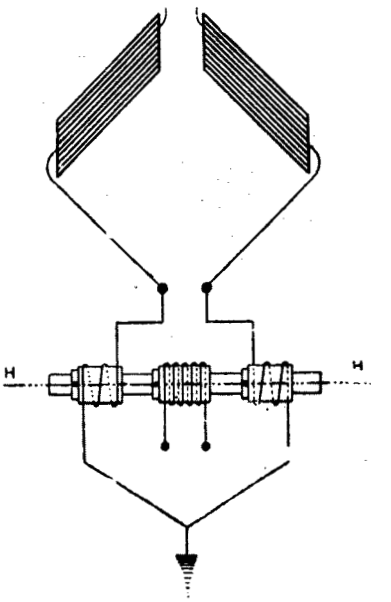


Fig. 5. Phased antennas (Artom, 1906).

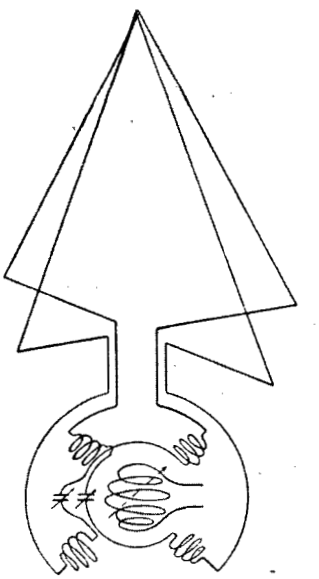


Fig. 6. Orthogonal loop antennas with goniometer for direction finding (Bellini and Tosi, 1907; Prince, 1912).

ANTENNAS IN PEACE AND WAR, 1910-1919

The period 1910-1919 saw the construction of many large, low frequency, high power antennas. In 1911 construction started of "Radio Virginia" at Arlington. One 600 ft mast and two 450 ft masts (reduced heights due to lack of funds!) supported a "flattop" antenna of two sections 355 ft long, and one of 240 ft, at the center of which was the downlead. The natural frequency was 137 kHz. The station was commissioned in 1913 with a 100-kW spark transmitter and a 35-kW arc transmitter. At this date reliable world wide communications were not possible. It is interesting to see the effect of World War I on this situation.

In July 1918, Haraden H. Pratt and George H. Clark selected a site at Monroe, NC for "the world's most powerful station" (which was never completed due to the war ending). The naval antenna was to be supported by 20 brick chimneys, 500 ft high, and contracts were placed at many of the brickyards of the South. Duplicate arc transmitters, each of 2 MW (average power, believe it or not) were to be installed.

In 1917, however, a "flattop" antenna was operated at 22 kHz at the Marconi station at New Brunswick, NJ. H. H. Beverage had described the 5000 ft by 600 ft flattop as being supported by 13 masts, 400 ft high, and as being "multiple tuned" at six points along the length, to increase the efficiency. "Multiple tuning" was introduced by E. F. W. Alexanderson of G. E. (Fig. 1).

A directional flattop also existed on a hill at Carnarvon in Wales, U.K. It was 3600 ft long and 500 ft wide. Ten steel tubular masts 400 ft high were arranged in four rows of 3, 2, 2, and 3 masts 900 ft apart. Four sets of seven stays of 3-in steel rope were used for each mast. Each mast was 3 ft 6 in diameter in the lower half and 2 ft 2 in the upper half, built in sections of 15 ft. Each stay-block was a 12 ft concrete cube, weighing 97 tons.

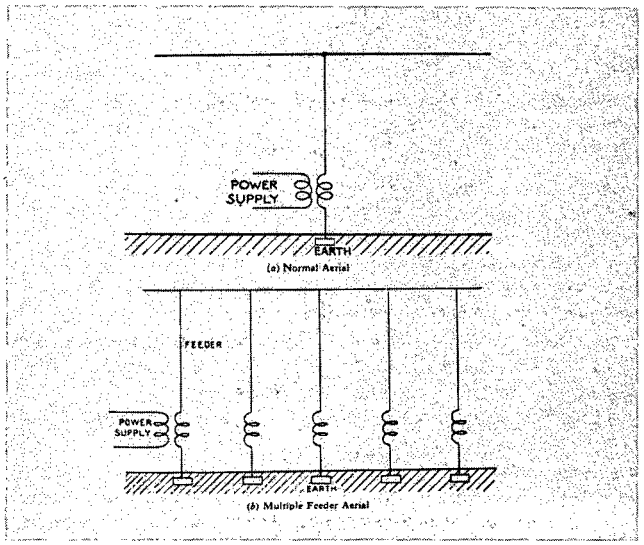


Fig. 1. Multiple tuned antenna (Alexanderson, 1917).

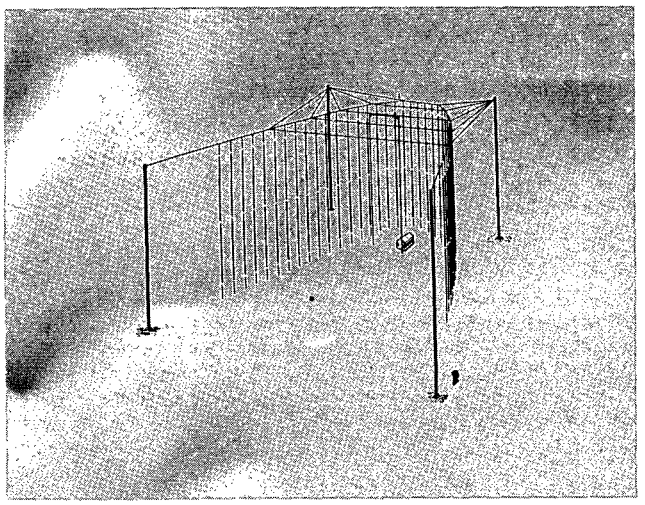


Fig. 2. Parabolic reflector with aerial at focus (Marconi, 1916–1921).

Both the U.S. and the (then) British Empire intended at the beginning of this second decade to set up world wide stations for global coverage with alternators or arcs at VLF, and with the above types of enormous antennas. Both projects were doomed before fruition, 1) by World War I, and 2) by some experiments of Marconi and Franklin with short waves.

In Italy in 1916 Marconi, "with the idea of utilizing very short waves combined with reflectors for certain war purposes" (secure communications), returned to wavelengths of 2 and 3 m generated by sparks in compressed air. He described the antennas. "The reflectors employed were made of a number of strips or wires tuned to the wave used, arranged on a cylindrical parabolic curve with the aerial in the focal line (Fig. 2). The transmitting reflector was arranged so that it could be revolved, and the effects studied at a distance on the reciever." Apertures up to 3½ wavelengths were used, and the measured patterns agreed with those calculated.

In 1917 using a 3 m wavelength and an aperture 2 m × 1.5 m, Marconi and Franklin obtained a range of over 20 mi; the receiver was nondirectional. In 1919 Franklin started to use vacuum tube generators, to suit which a 15-m wave was chosen. Speech was received on a mail-boat running between England and Ireland, to a distance of 78 mi. A link from London to Birmingham next yielded successful duplexed speech for a range of 97 mi. Marconi had observed "the important fact . . . that there was no rapid diminution of the strength of signals" beyond the horizon in the experiments. These results and his usual insight were to lead to major developments: 1) the discarding of long wave programs in favor of HF beam communications in the 1920's, and 2) the discovery of tropospheric scatter communications in 1932.

So much space has been taken here to relate how Marconi was to destroy his own long wave radiotelegraphy by crucial experiments on short waves between 1916 and 1920, that other antenna developments of an interesting character in this second decade must be carried over into a continuation of this story in the next section.

ANTENNAS IN PEACE AND WAR, 1910-1919 (Continued)

Apart from the long wave developments and short wave research described in the preceding section, the period 1910-1919 saw the flourishing development of radio techniques in new fields. Aeronautical radio, including voice communications and navigational direction finding, from a fitful start (Fig. 1) became established. By 1919 the U.S. Navy NC-4 aircraft and the British dirigible R34 had made successful radio-assisted transatlantic crossings. Fig. 2 indicates to Long Islanders that the R34 landed at Mineola from Scotland.

Ships and submarines (Fig. 3) adopted cage antennas introduced by the British Navy. In 1918 the U.S. Navy found that a submarine submerged at 21 ft could receive high-power long-wave transmissions over long distances.

Radio remote control of ships, torpedoes, aircraft, and drones had its origins in this decade. Hammond and Meissner launched the marine applications as early as 1912 (Fig. 4), while Cooper-Hewitt and Sperry introduced gyro-stabilization for missiles in 1915. In direction finding, the 180 degree ambiguity was removed by the use of a sense antenna. In World War I both sides used DF extensively for interception. location and tracking of ships, aircraft, dirigibles, and troop movements.

The long-sought radiotelephone reached practicality with the advent of the vacuum tube. In 1910 the voice of Caruso was broadcast by DeForest, who also broadcast election bulletins in 1916. In the same year, music was broadcast daily (except Sunday) at New Rochelle, NY. In 1919 President Wilson broadcast from sea as he returned from the Peace Conference. In Europe, Capt. De Donisthorpe carried out broadcasts in 1917, and the Marconi company conducted tests in 1919. All of these preliminaries were to lead to extensive antenna engineering for broadcast transmission and reception in the 1920's (next section).

Long-wave receiving antenna experiments were carried out to improve S/N ratios and reduce interference. Long wire antennas were laid along the ground, or buried, or submerged in fresh water. On the ground, Weagant's thin loops and Alexanderson's straight wires (Fig. 5) contained frequency, phase, and amplitude control circuitry which presumably yielded nulling and directivity. Underground antennas were alleged to reduce static. In 1917 Lt. Hoyt Taylor showed that an antenna in fresh water was ten times better than one laid underground. In the war, underground signaling using power buzzers provided communications

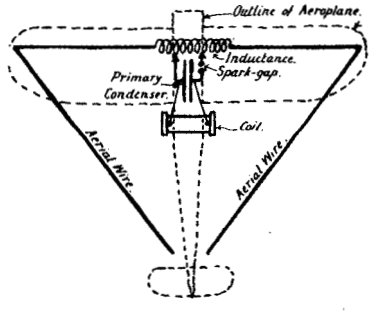


Fig. 1. Aircraft transmitter and antenna (1910).

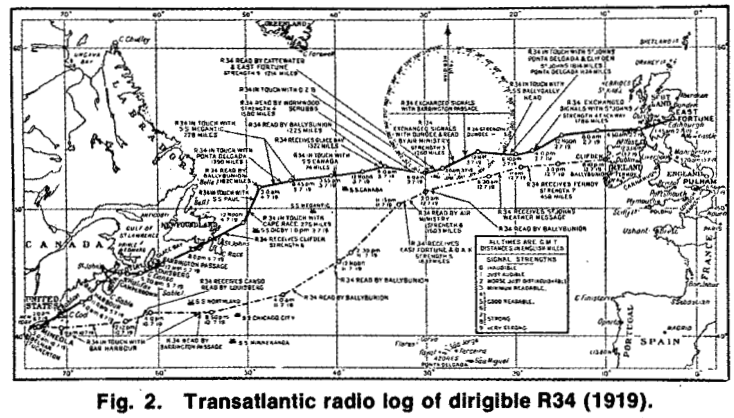


Fig. 2. Transatlantic radio log of dirigible R34 (1919).

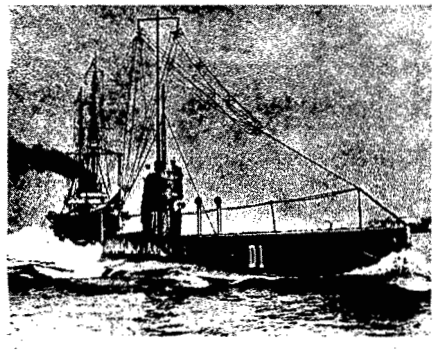


Fig. 3. Cage antenna on submarine (1915).

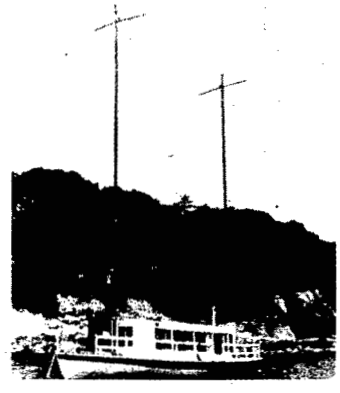


Fig. 4. Remote control antennas for houseboat control (1912).

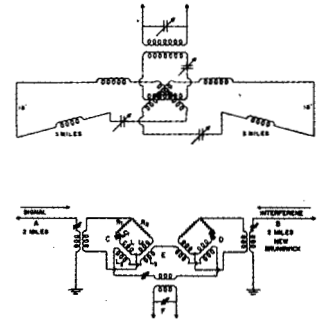


Fig. 5. (a) Directional-loop antennas (Weagant, World War I). (b) Directional dipole array (Alexanderson, World War I).

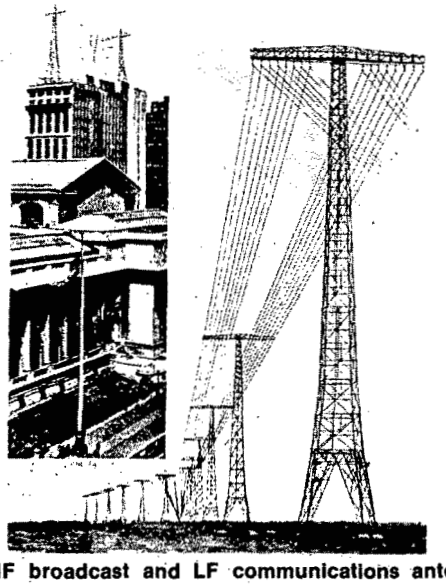


Fig. 1. MF broadcast and LF communications antennas of early 1920's (RCA).

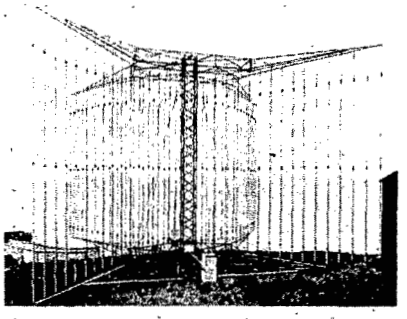


Fig. 2. 70 MHz parabolas for estuarial beacon (Franklin, 1920).

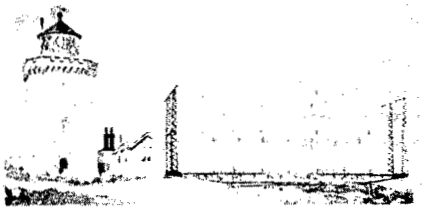


Fig. 3. Lighthouse beacon using Franklin array (1921).

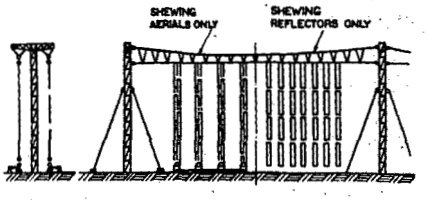


Fig. 4. HF Franklin array (1924).

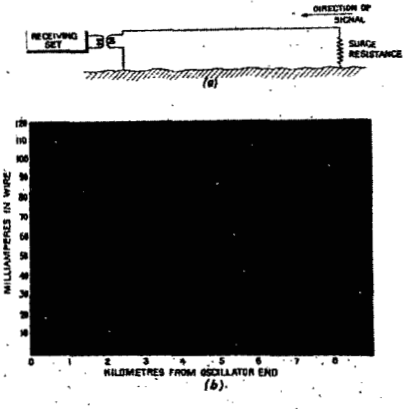


Fig. 5. Beverage wave-tilt antenna (1923).

from forward trenches to posts 1000-3000 yd in the rear.

The next section will deal with the post-war antenna engineering of the 1920's, when the Marconi-Franklin HF beam antennas captured the long distance communications field, and broadcasting put antennas on roof-tops and in backyards throughout the civilized world.

THE RADIATING TWENTIES, 1920-1929

It is possible to discern the arrival of system engineering in the period 1920-1929. The antennas began to take specialized forms suited to their applications. The developments may therefore be classified by application areas, although cross fertilization always takes place.

Broadcasting

Radiating intelligence and entertainment to all and sundry began seriously and developed into a boom, despite Marconi's dismay at this misuse of his invention. The early antennas were makeshifts derived from the earlier point-to-point communications designs (Fig. 1). Later the coverage advantages of the halfwave mast radiator became appreciated. In 1927 directional arrays were initiated. Home receivers also used couplers to electrical house wiring, with water pipes for ground connections, although most backyards carried *L*-type wires, and had ground stakes.

Short wave broadcasting to world wide ranges also commenced in the mid-twenties. Transmitting antennas became directional following the communications varieties for HF described below. Receivers required "all-wave" antennas using empirical broad-banding for MF and HF. A few used loops for MF and LF.

Communications

The outstanding innovation in the twenties was Franklin's planar array of loaded wires with a wire reflector, fed by experimentally developed coaxial lines, for the successful world range HF communications he developed with Marconi. Starting from VHF parabolas (Fig. 2) Franklin made a lighthouse beacon array (Fig. 3), then launched into his larger HF arrays (Fig. 4). A Marconi proposal in 1924 led to operational feasibility in 1926, and by 1929 the British cable interests had to amalgamate with the radio service. The HF Beam System had conquered the projected Long Wave High Power Imperial Wireless Chain which never saw the light of

day. Antenna directionality had triumphed. This phenomenon we shall see repeated in the decades following.

In the U.S. the Navy experimented with and eventually adopted HF communications. Lt. Cmdr. Byrd in 1926 flew over the North Pole in an aircraft which carried an HF transmitter. The dirigible USS Shenandoah had also used HF communciations as early as 1923. By 1925 the USS Seattle had maintained HF communications on a voyage to Australia. The parallelism that seems always to have existed between the R & D of the U.S. Navy and that of the British Marconi company is historically remarkable.

A bright highlight of 1923 was the directivity of a single long low wire over poor ground, developed by H. H. Beverage of RCA for long wave reception. This "wave-tilt" antenna (Fig. 5) was erected both on Long Island and in Fife, Scotland.

Navigational Aids

The U.S. Navy had introduced an aircraft LF radio range in 1919; at the same time Franklin was developing a VHF coded estuary beacon in Scotland. By 1926 Smith-Rose had established the superiority of Adcock's 4-monopole DF system. An Adcock-type four-course radio range was installed at Hawaii and San Francisco in 1927. In 1928 Diamond and Dunmore of NBS developed the first blind-landing or ILS system.

Research

Taylor and Young of NARL detected moving objects by radio in 1922, presaging radar. Yagi and Uda in Japan evolved an endfire array containing parasitic directors in 1928. Marconi in 1927 at New York foresaw free-space power transmission by highly directive antennas.

The next section will describe how the new VHF spectrum was to lead to antenna developments for radar and television as well as the established radio services.

THE RETURN TO VHF AND MICROWAVES, 1930-1939

The following innovative developments in radio-electronics in the 1930's saw a return to antenna configurations and techniques which had originated in the 1890's (see the second section).

- 1931 Microwave link established between France and England used reflector antennas at 17 cm (IT&T).
- 1932 Tropospheric scatter communication discovered by Marconi cruising in Mediterranean, using reflector antennas at 50 cm. Microwave link was also installed at Vatican by Marconi.
- 1935 VHF radar programs of NRL and RAF used dipole array antennas. FM broadcast demonstrated by E. H. Armstrong on 2.5 m.
- 1936 TV broadcast service opened in London, England, using ring arrays of dipoles at 45 MHz. Hollow-pipe waveguides investigated by Bell System using centimeter waves.
- 1937 Radiotelescope reflector built by G. Reber used cavity feed at 160 MHz.
- 1938 Waveguide radiators investigated by W. L. Barrow and E. M. Greene at decimeter waves.
- 1939 Horn Antennas extensively investigated in U.S. at decimeter and centimeter waves. Slot antennas invented and tested at VHF.

From the above chronology it is clear that the 1930's saw the evolution of systems using VHF (1-10 m) and microwaves (below 1 m); that is, a return took place to the original region of the spectrum opened up by Hertz and his immediate successors. Consequently, many of the antennas that appeared were "classical" in type. Hertz had introduced the parabolic reflector (the paraboloid being preferred in the 1930's and subsequently). Lodge had developed waveguide radiators and had discovered waveguide modes, the theory of which had received attention by J. J. Thomson and Rayleigh. Chunder Bose had invented the electromagnetic horn.

The dipole and the loop were Hertz's inventions. Arraying had been proposed by S. G. Brown in 1899 and implemented by Artom in Italy in 1906 (third section).

The new radio-electronic systems of the 1930's, using Hertzian wavelengths, encompassed fundamental systems still with us today—TV and FM broadcast, microwave communications, tropospheric scatter communications, VHF and centimetric radar, radio-astronomy, and improved navigational aids. If one looks at the many antennas currently used today, it is seen that many are of classical origin, antedating the wire configurations evolved by Marconi and his followers. An inspection of the illustrations of this series shows that, with the exception of Franklin's wire parabolas, there were no parabolic reflectors from 1900 to 1930, and that waveguide and horn radiators faded out about 1900, and did not reappear until 1938. The dielectric lens antennas, evolved in the 1890's, saw a fitful rebirth in the 1940's, but had minor utilization until the 1950's, when millimeter wave generators became available.

The most important technical advance in the 1930's was, in the opinion of the writer, the invention of the resonant slot. This was a device which was both an aperture radiator and a resonant structure. Its novelty was major. Nothing as important had appeared since Hertz invented the dipole and the loop, and Lodge and Bose experimented with open-ended waveguide radiators. The slot antenna was rediscovered in the early 1940's, but its origins are earlier. For example, in 1939 A. D. Blumlein received a patent for a slotted tube, excited either magnetically by a coupling coil, or electrically by direct connection of a balanced line to the edges of the slot. The tube diameter was of the order of one-thirtieth of a wavelength. The radiated polarization was perpendicular to the length of the slot.

The illustration shows an open-ended slot excited at one end. However, Blumlein said, "Alternatively, connections may be made to the opposite edges of the slit at the center of the conductor, short circuit connections being provided at the opposite ends if desired." This sentence describes a line-fed resonant slot as we now know it. Investigations were carried out by the inventor, of patterns and gain at different

frequencies, of slot configurations, including different feed and tuning arrangements. A linear array of slots was proposed. The phenomena of traveling waves and standing waves, of the phase velocity control by the shunt inductive and shunt capacitive loading, and of the attenuation and polarization, were all understood by Blumlein. Multiple slits around a tube of greater diameter were also proposed. Blumlein's slits and slots were destined to be fed in other ways in later years; communications, radar and navaids were to employ them extensively whether on ground-based, airborne or space-borne systems. The resonant slot was as significant an invention as the resonant dipole, and gave the 1930's a forward look which offset the backward trend to the reflectors, waveguides, and horns of the eighteenth century. Both developments were however to flourish in the coming decades.

The 1930's saw many antenna developments at MF and HF, of lasting value. Single and two or more tower radiators entered MF broadcast. Many varieties of arrays appeared in HF point-to-point communications. Bruce's rhombic or diamond antenna, and the biconical antenna (Carter, Wheeler, Schelkunoff) introduced wide-band structures. History was made in 1937 by MUSA, an array of in-line rhombics steerable in elevation by IF phase shifters and studied in depth by the Bell System. Space prevents justice being done to these lower frequency developments since the highlight of the 1930's was the trend to VHF and microwaves.

In the next section we shall see that the trend became a headlong rush brought about by World War II and the ensuing social needs of the postwar 1940's.

CENTIMETER-WAVE ANTENNAS, 1940–1945

The trend to VHF and microwaves in the 1930's accelerated into a rush in the early 1940's, brought about by World War II. The secret radar experimenting of a few groups became national objectives involving tens of thousands of people, both in the U.S.A. and in the U.K. There were thousands of workers in the antenna field alone, and the output was prodigious.

In the mid-thirties, the advantages of cm waves in affording high resolution radar had been appreciated, although little investigation seems to have been carried out, despite the existence of cm-wave communications—an unexplained mystery. The need for long range kept the wavelengths long, until on February 21, 1940, Boot and Randall in England obtained 400 W average power from a 6-cavity magnetron on 9.8 cm, making long range cm-wave radar possible. By October 10, 1940, BTL had made the first U.S. cavity magnetron, based on British information.

To simplify the description of the antenna developments, we shall summarize how the progress of the war years added to configurations and techniques at cm waves. It will be recalled (second section) that cm-wave antennas had been evolved by physics professors in the 1890's, in their investigations of the "Maxwellian" or "Hertzian" waves. Dipoles, loops, reflectors, lenses, waveguide and horn radiators had all appeared, and arraying had been proposed. Arraying, as we have seen, later developed at HF and VHF, and the new element, the slot, had arrived by 1939. The cm-wave antennas can therefore be classified as reflectors and feeds, waveguide and horn radiators, slots and slot arrays, lenses and feeds, and a new class of end-fire dielectric antennas.

1) Reflectors and Feeds: Fan beams were produced by cylindrical parabolas or by cut paraboloids. A thin strip parabola with top and bottom plates was a "pillbox" for polarization perpendicular to the plates, or a "cheese" for polarization parallel to the plates. The antennas were used alone, or as line feeds for cylindrical parabolas. Shaped beams (cosecant) were formed by distorting a reflector, or by using a multiple feed system. Lobing beams (Brit. "split") were obtained by switching between two adjacent feeds for accurate direction finding.

Beam scanning without bodily antenna motion was realized by providing a cylindrical parabola with a line source incorporating a mechanical scanner, which either rotated a feed, or imparted linear phase shift directly at the aperture of the line source. Paraboloid feeds were open-ended waveguides with flanges, or small horns, or dipole and reflector combinations driven either by waveguides or coaxial lines.

Grating reflectors were developed using tubes or slats. Horizontal polarization was preferred. Plastic covers for antennas, or radomes, were developed with low absorption and reflection properties.

2) Waveguide and Horn Radiators: The rectangular waveguide, of nominal ratio 2/1, became the transmission line for cm-waves, largely because of its low losses and high power capacity. The open end could be fitted with a surrounding flange, or tapered, to form a pyramidal horn, giving a broad beam for surveillance, or for feeding a reflector or lens. Horns of the sectoral type of the 1930's were also used, giving fan beams. The excitation of two modes in a small horn was found to control the amplitude distribution at the mouth.

The "hoghorn" was a small half-pillbox fed by an offset waveguide, found suitable for feeding a cheese antenna.

3) Slots and Linear Arrays: The properties of the resonant slot became understood. Slots on either the narrow or the broad face of a rectangular waveguide furnished traveling wave or resonant arrays, depending on whether the far end of the guide had a matching termination or a shorting plate. Dipole arrays were also driven by waveguide. The slotted waveguide arrays were ideal for feeding a cylindrical reflector, whether parabolic or of shaped beam type. Two-dimensional arrays of slotted waveguides were also built.

The sensitivity of the beam direction to either the broad dimension of the waveguide, or the frequency, was investigated. A variable width scanner using 250 dipoles at 3.2 cm (U.S. "Eagle") gave a ± 30 deg scan of a beamwidth between 0.4 and 0.5 deg. In England a slot array succeeded in giving a cosecant pattern. Slots of dumbbell form were also investigated.

Slots were cut in cylindrical waveguides fed by circularly polarized waves to produce omnidirectional patterns with horizontal polarization for radar beacons. Dipole arrays served the same purpose.

4) Lenses and Feeds: Phase correction of a horn was achieved in 1941 in England by fitting a set of metal plates either of constant spacing and varying depth, or of constant depth and varying spacing, to a horn. In the U.S. a small feed horn illuminated a set of profiled metal plates of constant spacing, spaced from the horn. Both approaches gave birth to a new device, the "metal lens," having an index of refraction less than unity, or a variable index less than unity.

Dielectric lenses were also investigated. Circular lenses saw little use, but thin strip lenses were fitted to sectoral horns.

5) Dielectric Antennas: In 1910 dielectric waveguide theory had been developed in Germany. Preliminary work in the late thirties led to the development, in the early 1940's, of dielectric end fire antennas in the U.S., England, and Germany. A solid rod, of tapered type, of polystyrene ("polyrod"), about 6 wavelengths long, gave a 25 degree beam. A 14×3 array of polyrods in the U.S. was scanned electrically by mechanical phase shifters. Smaller arrays were used by Germany for search antennas. Dielectric thin-walled tubes of about two wavelengths diameter gave similar beamwidths.

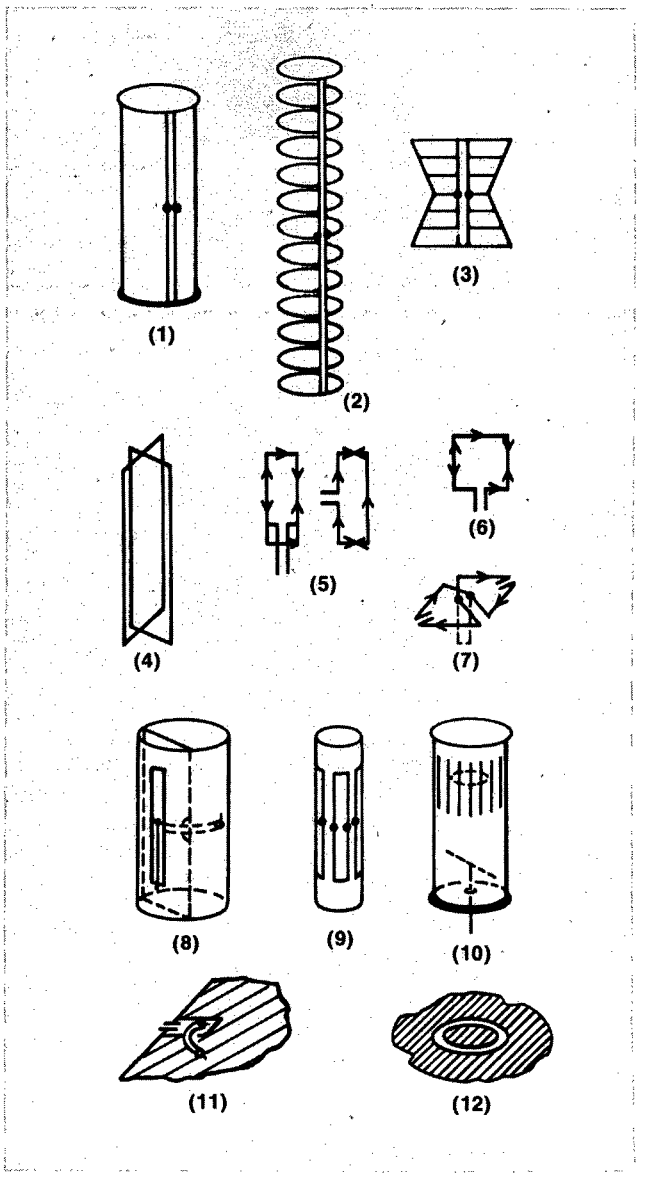
The next section will show how VHF and microwave antennas entered into the post-war applications of radio-electronics in the late 1940's.

VHF SLOTS, LOOPS, AND DIPOLES, 1946-1949

Antenna history is the history of spectrum utilization. As different regions of the spectrum are opened up at different epochs in time, antenna evolution always takes place, sometimes minor, often major. The reasons why different spectral regions have received special emphasis at different times in the past are many, complex, often unpredictable, but always entirely rational. Basically, spectral expansion is dominated by human motivation and the current level of technical feasibility. Thus, radar was needed in the early 1940's, and primitive systems existed in the late 1930's, so the war years saw a great centimetric breakthrough. In the early post-war years, the motivation swung to the old dream of seeing pictures by radio, or as John L. Baird called it, "tele-vision." In the late 1920's Baird's 30-line pictures were broadcast as a regular MF system. During the 1930's the need for higher resolution and bandwidth led to a move to VHF with complete success. World War II snuffed out the promising new medium. From 1946, however, the shackles were off, and a VHF-TV boom set in. Also Edwin H. Armstrong had shown how VHF-FM could yield surpassing audio fidelity, and a parallel FM boom ensued.

These social objectives and the level of VHF feasibility were to lead to new looks in antennas. Notably the resonant slot antenna (seventh and eighth sections) was to see further development. Blumlein's slotted tube was found by RCA to be more effective omni-directional radiator if the circumference approximated a half wavelength (Fig. 1). Alford showed that the cylinder could be polarized, consisting of stacked loops fed by a slot (Fig. 2). A slot with finite flanges, instead of a surrounding metal sheet, was evolved by Masters as a part-slot, part-dipole radiator (Fig. 3). The Workshop Associates (US) and Ramsay (UK) both developed a "skeleton slot," in reality a thin rectangular loop with inphase currents in the short sides (Fig. 4). This "wire-slot" is physically the same as a folded dipole (Fig. 5), but is shunt excited instead of series excited. A square loop driven in this mode was the "quad" element devised by Orr (Fig. 6); it contrasts with Alford's resonant loop of Fig. 7.

To secure omnidirectional patterns in azimuth from flanged or wire slots, orthogonal pairs are used, fed in phase or in quadrature.



Cylinders with multiple slots, as foreseen by Blumlein, appeared for VHF broadcasting, and also for VHF ground-based beacons for aircraft. Monteath's cavity-backed folded and stubbed broad-band matched slot (Fig. 8) was developed for British FM broadcast, the later antennas consisting of eight tiers of four slots in a 5 ½-ft diameter cylinder. For the aircraft ORB (later VOR) beacons, Alford used four line-fed slots in a slim cylinder (Fig. 9), while Ramsay excited twelve slots in a cylindrical waveguide, by an internal loop for an omnidirectional pattern, and a rotating dipole for a rotating figure of eight patterns (Fig. 10).

For aircraft the flush-mounted slot became the standard "suppressed" antenna. Cavity-backed and loaded slots appeared in the 1940's in profusion. More basic configurations, however, were the "notch" and "nitch" slots, with one end open, developed by Johnson at RAE in England. Cut in the edge of a half-plane or finite sheet, the notch was nominally quarter-wave long, the nitch being smaller and capacitively loaded at the open end (Fig. 11). These varieties could be used from 2.5 to 500 MHz for aircraft services! Another fundamental slot geometry was the circular or "annular" slot with a radial electric field, described by Pistolkors of the USSR in 1948 (Fig. 12). If the diameter is small the pattern is that of a monopole when the slot is cavity-backed.

An interesting broad-band (in these days) folded dipole, made of strip instead of rod, was developed by Willoughby in the 1940's and later used in British television transmitting arrays. With regard to the broad-banding of antennas in general, considerable progress had been made in the 1930's for communications, and in the 1940's for reconnaissance, surveillance, and countermeasures. In the 1950's, however, a major breakthrough in broad-banding was to take place, and will be one of the highlights to be described in the next section.

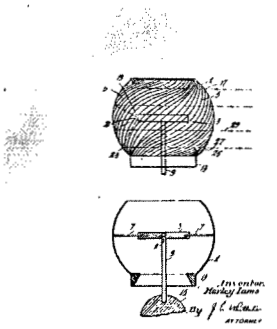


Fig. 1.

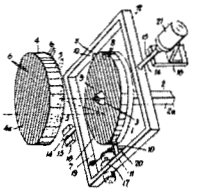


Fig. 2.

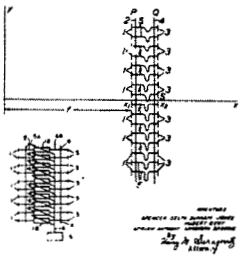


Fig. 3.

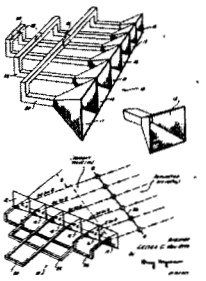


Fig. 4.

DECADE OF INVENTIONS, 1950-1959

Reflector Antennas

As radar antennas became larger, windage, weight, and the slow rotational speeds led to a continuation of the wartime research on "inertialess" scanning. Pioneer work had been carried out in the early 1940's on spherical reflectors, feed-motion scanners, and phased arrays with mechanical phase shifters. This work was extended in the 1950's to cover improvements in reflectors and in feed scanners, moving or switched, and by the end of the decade resulted in a marriage of the phased array with the reflector antenna, and a replacement of all mechanical motion by truly inertialess electronic scanning.

Nevertheless one of the basic problems was not solved, viz. the provision of 360 deg of azimuth scan with as much elevation scan as possible. This problem is not, even today, adequately solved. In the 1950's two partial solutions were found, each based on the theoretical rotation of a parabolic curve about a vertical axis parallel to the latus rectum. If the axis is in front of the parabola, twice the focal length away from the vertex, a closed barrel-like, toric surface is obtained, while if the axis of rotation is behind the parabola a vase-like surface is generated. In either case there is an elevation focus on a circle, either inside the barrel, or outside the waist of the vase. In the case of the vase (or "hourglass" as it is now known) a small phased array on the focal circle can be arranged to produce a collimated beam from the reflector to space. A circular array can be programmed to give 360 deg scanning.

In the case of the barrel, transparency was given to the surface by using polarization. In 1947 Iams had devised a "fishbowl" radar beacon by laying wires on a spherical surface, polarized at 45 deg to the equater. An incident wave polarized at 90 deg to the wires enters the fishbowl and falls on a concave side whence it focuses at half the radius. A ring reflector (Fig. 1) returned the energy retrodirectively to the radar receiver. Inventors in the early 1950's converted Iam's beacon to an antenna ("Birdcage," "Helisphere") by replacing the ring reflector by a rotating feed or multifeed, securing 360 deg azimuth scanning with some elevation scanning; others developed the parabolic torus version using an offset half-barrel to avoid feed obscuration. The barrel-type antennas suffered from some excess of aperture size, the diameter being approximately twice that of a conventional antenna of the same beamwidth.

Another use of polarization appeared in the "twist-reflector paraboloid" invented by Cochrane and Mariner in England (Fig. 2). The collimated beam from a polarized paraboloid was reflected by a plane twist-reflector or polarization twister (Zehnder, 1894), and passed out through the rear of the

paraboloid. Tilting the transreflector gave a large scan angle.

Several quasi-optical wide-angle reflector systems were developed in the 1950's, and included the coma-corrected zoned reflector, the coma-corrected metal-lensed reflector, the Schmidt lens-corrected spherical mirror, and the mangin mirror. NRL (1953) had introduced the parabolic torus to microwaves. Raster scanners were also evolved giving microwave images, and included organ pipe scanners and a ring-switched microwave Nipkow Disk.

Jones, Gent and Browne (1958) contributed a far-reaching technique to the lensed reflector by inventing a programmable reflecting array containing phase shifters or delays lines, the array being free-space fed by a feed. The patent shows a "bootlace" lens array of two surfaces of dipoles interconnected by variable phase shifters. (See Fig. 3.)

A reflecting array which was autocollimating or retrodirective (Fig. 4) was invented by Van Atta in 1955. Some years earlier (1952) retrodirective lenses and optical reflectors with focal region processing had comparable properties.

Lenses

Artifical dielectric lenses of several types were developed. Expanded and/or loaded dielectrics became state of art.

One-dimensional and two-dimensional scanning Luneburg variable-index lenses reached feasibility.

Coma-corrected, zoned metal, and dielectric lenses of quasi-optical type gave wide-angle scanning by feed motion or multifeed.

Microwave optical systems were developed, particularly at mm waves, and yielded eyepieces, focus splitters, phase contrast analogs, Fourier transformers, interferometers, spectrometers, polarimeters, as well as free-space hybirds, duplexers, directional couplers, attenuators and other analogs of waveguide components.

The Reggia-Spencer ferrite phase shifter in waveguide was described (1957).

Geodesic lenses constructed from two closely-spaced parallel surfaces were developed and included the "tin hat" type Luneburg version.

Ultra-Wideband Antennas

Spiral slot antenna (Turner, 1955).

Equiangular spiral antenna (Dyson, 1955).

Conical spiral antenna (Dyson, 1959).

Toothed vee log periodic antennas (Duhamel and Isbell, 1957).

Log periodic feeds for reflectors and lenses (Duhamel and Ore, 1959).

Arrays

Commutated circular arrays (Wullenweber, hourglass).

Slotted waveguide arrays, phase or frequency scanned.

Multielement arrays with ferrite phase shifters.

Arrays providing multiple independent beams.

Leaky & Surface Wave Antennas

The Yagi array of 1928, and the polyrod, dielectric tube, and long-slot waveguide radiators of the 1940's led to extensive R&D in the 1950's on the wave mechanics, so to speak, of these and allied configurations. As a result, upwards of 30 (!) new configurations appeared and established leaky and surface wave antennas permanently in antenna technology, including the ultra-wide-band varieties listed above.

The next section will describe the extrapolations and new techniques which advanced the antenna state of the art in the 1960's.

NEW HORIZONS FOR ANTENNAS, 1960-1969

The theme of this series of monographs has been dedicated to *innovation* on the unfolding history of antennas. "Innovation" is described by Webster as primarily "the act of innovating or effecting a change in the established order; introduction of something new." As we have seen, each decade has been lively with innovative antenna developments, and the 1960's were no exception. Space technology, coherent light, computer advances, and spectrum expansion were new factors opening up wider horizons for antennas. The number of contemporary antenna types and techniques is now so large that a catalog, rather than a single page, is necessary for their listing. Fortunately, when encumbered with detail, we can move to a higher level of generality, to reduce the complexity. Here, then, we shall look at antennas in systems, instead of antenna types, and try to distinguish the innovations of the 1960's in the systems, and the antenna potential for the 1970's.

There were four key dates in the 1960's worth remembering. In 1960 T. H. Maiman demonstrated the first ruby rod laser, in 1963 E. Leith produced the first offset holograms using a laser, in 1965 Comsat's first synchronous satellite, Early Bird, was operational, and on July 20, 1969, men and antennas were on the moon. All of these dates are milestones in the history of electronics.

In the cases of the synchronous satellite and the moon landing, the significance of antennas is apparent. The laser and holography, however, also affected the future of antennas. For the laser was an "energetic" antenna system, a transmitter which itself radiated a beam; further, as Winston E. Kock has pointed out, optical holography has in principle the features of the earlier coherent, side-looking airborne radar at microwave frequencies. Georges A. Deschamps has indiciated that we may even obtain holograms at the lower radio frequencies. The theory of holography is the same interference and diffraction theory as used in antenna analysis.

Antennas have been traditionally used for two purposes, either the obtaining of information or, less commonly, for transmitting useful power, as in medical electronics, or in the growing industrial utilization of microwave power. The laser suddenly indicated that orders-of-magnitude advances in information transmission were possible, whether in respect to bandwidth or beamwidth, and that the classical generation, transmission and utilization of electrical power via circuits could be implemented by waveguide, or even beam power transmission, and by diffractive power handling for utiliza-

tion, which has all the convenience, speed, and sophistication of optical techniques. From the apparent fantasies of the early 1960's, the end of the decade has seen a matter-of-fact acceptance of the realities. Ultra-wide bandwidths, ultra-sharp beams, ultra-high power densities, ultra-low stray radiation, very wide angle scanning, and so on characterize and will continue to characterize the evolving radiation systems and antenna systems. "Energetic antennas" can be expected for space applications, for hostile terrestrial environments, undeveloped countries, and remote powering generally.

Marcel J. Golay has said that it might take 100 years (from the 1950's) to bridge the radio-to IR gap. Today there is still no super-power engineering between 1 cm and the visible spectrum. In the 1920's C. S. Franklin used to say he had to wait for the tubes. In the 1970's we may still have to wait for the generators, which will likely be sources incorporating antennas. Throughout radio history, the opening up a new spectral region has brought gains in science, technology and business. In antennas, spectral expansion always leads to innovations. The mm and sub-mm antennas, presently quasi-optical, can be expected to change, as super-power becomes available, in whatever time decade. Even now there is a need to determine the electrical properties of materials at these frequencies, perhaps even to fabricate new compatible materials for the future.

In the 1960's the microwave phased array with the computer gave radar a cybernetic trend in the scope and versatility of the command function, and in the EDP or interpretative function. In space communications, antennas became computer-dependent. In navigation, whether space, airborne or terrestrial, the new needs made the computer essential, and has led to mission and traffic prognostications for antenna and systems for years far beyond the 1970's. The computerized antenna of the 1960's, already adaptive, active, and essentially becoming multidimensional, will generate descendants essential to the greater goals of the coming decades, as phased arrays on the moon, space beacons and relays, automatic landing of space or hypersonic vehicles, or of supersonic aircraft, automobile and railroad automation, and so on.

Reference must be made to "interface" and "immersed" antenna developments of the 1960's. An interface antenna is an antenna laid on, or in close proximity to a medium, while an immersed antenna may be buried in the ground, or immersed in water or contained within a plasma. All these varieties were developed, for reasons varying from the investigation of ground loss resistance, to requirements for subterranean radar or signaling, or to secure radiation through plasma, as at re-entry. Even the atmosphere received new attention as a "non-free-space" medium, because of propagation anomalies in a tenuous medium affecting the "free-space" characteristics of the antennas. Interface antennas entered the medical, scientific and industrial fields also. This writer even suggested an interface VHF radar antenna on the face of the Great Pyramid for probing its structure! Archeologists would dig less if radar were used for locating ancient sites and artefacts near the surface.

A neglected area of antenna utilization is in the use of EM radiation to stimulate the growth of plants and crops. Having regard to the pockets of famine anticipated in the 1980's, it is possible that agriculturalists will look to man-made spectral energy to accelerate food production.

The antenna configurations which excited the greatest engineering interest in the 1960's were: 1) the log periodic dipole arrays which caught the TV reception market, 2) the subminiature integrated dipole and monopole antennas which are expected to mature in the 1970's, and 3) the phased arrays, bootlace lenses, and reflectarrays using microwave integrated circuits. Greater scientific interest attached to the successful introduction of cryogenic antenna systems, and to the possible application of elastic surface waves for electronic scanning. Liquid and plasma antennas saw little development. ■

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